BEYOND THE STANDARD MODEL

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Review of recent developments in attempts to go beyond the Standard Model is given. We concentrate on three main unresolved problems: mechanism of electroweak symmetry breaking, expected new physics at the TeV scale (mainly SUSY) and the origin of the Dark matter.

Keywords: Electroweak symmetry breaking; Supersymmetry; Dark matter

1. Introduction

The Standard Model of fundamental interactions, which is the starting point of all attempts to look for new physics at high energies, was established as a result of mutual theoretical and experimental efforts and represents a solid construction one can be proud of. Today we face the situation which I would call the HEP paradox: unlike a usual situation in history when a new theory emerges as a response to unexplained new phenomena, a modern experiment shows no deviation from the SM and the motivation to go beyond it comes merely from our desire to explain some features of the SM and our views on unified theories.

During the last decade there were numerous experimental attempts to find physics beyond the SM. Search was made for

- low energy supersymmetry
- extra gauge bosons
- axions
- extra dimensions
- deviation for the unitarity triangle
- modification of the Newton law
- free quarks
- new forces/particles
- violation of baryon number
- violation of lepton number
- monopoles
- violation of Lorentz invariance
- compositeness

All of them have failed so far.

Thus, going beyond the SM one has no hint from experimental data and has to follows one's own preferences and/or fashion. Still there are some common topics that seem to be of mutual interest and importance. Below I will concentrate on three main problems of modern high energy physics.

2. Problem #1: Mechanism of Electroweak Symmetry Breaking

Being very successful in describing three fundamental forces of Nature the SM does not shed light on the origin of masses. The mechanism of electroweak symmetry breaking is still not confirmed. So the question is: is it the Higgs mechanism or an alternative one?

The standard Higgs boson searches are both direct and indirect. Indirect limits come from radiative corrections and the direct one comes from the Higgs boson nonobseravation at LEP II (see Fig.1) [1] The modern limits on the Higgs boson mass are [1]:

$$M_h = 89^{+42}_{-30}\ GeV\ @\ 68\%\ CL$$
$$M_h < 175\ GeV\ @\ 95\%\ CL$$
$$for\ m_{top} = 172.5\ GeV$$

So if the Higgs boson is really there, we will see it soon.

However, one may look for alternatives. They are:

- Two-Higgs doublet models [2].

These models are exploited for many years

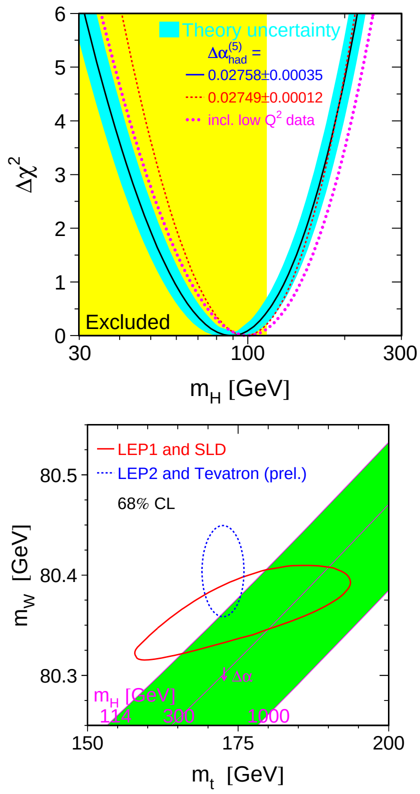


Fig. 1. Current indirect limits on the Higgs boson mass

and have a reach bibliography. The main difference from the SM is the extra Higgs doublet that introduces new free parameters including the complex ones which would lead to new sources of CP violation. Due to the mixing of states one can make the lightest Higgs boson almost sterile since its interaction with the Z-boson is suppressed by $\sin(\alpha-\beta)$ that allows one to have the lightest Higgs mass below 100 GeV without contradicting the modern limits.

• Inert Higgs model [3].

In this model, the inert Higgs doublet has neither vev nor couplings to quarks and leptons. After mixing the lightest particle might compose the Dark Matter while the usual Higgs boson is heavy (>400 GeV) and does not contradict the precision EW tests.

• Little Higgs models [4].

This class of models represents a new idea of protection of the Higgs mass against radiative corrections alternative to supersymmetry. The Higgs bosons here are considered as pseudo-goldstone bosons of some large group similar to the π-mesons in chiral theories. In this case, originally the Higgs bosons are massless and obtain their mass radiatively, but quadratically divergent contributions are not generated and one is left with the log hierarchy. For this to happen one needs the so-called collective symmetry breaking and thus a larger gauge group, usually $SU_2 \times SU_2$ or $SU_3 \times SU_3$. This leads to new heavy states with masses around 1 TeV. The collider signatures are similar to SUSY albeit have a different angular dependence due to a different spin structure [5,6]. To solve the problem of the Dark matter, one introduces new parity, called T-parity, similar to R-parity in SUSY models which allows one to get a stable light particle [7].

• Twin Higgs model [8].

It is similar to the Little Higgs model and also treats Higgs boson as a pseudo-goldstone particle, but has discrete symmetry, twin symmetry, like mirror of L-R symmetry, which allows one to improve phenomenology. One also has a supersymmetric generalization of this model [9,10], though the LH model was introduced as an alternative to SUSY.

• Gauge-Higgs unification models [11].

In this class of models one assumes the existence of extra space-time dimensions. Then the gauge field has extra components which from the four dimensional point of view can be considered as scalar particles and one treats the Higgs boson in such a way. One uses discrete symmetry to protect the Higgs mass from the radiative corrections similar to the Twin Higgs model. In order to get chiral matter and the Higgs boson in fundamental representation, one needs an orbifold compactification of extra dimensions. This leads also to an infinite tower of K-K excitations for W and Z bosons with masses in the range of 500 GeV - 1 TeV and extra heavy scalar fields.

• Higgsless models [12].

In this case one also exploits the idea of extra dimensions with non-flat (warped) geometry. Electroweak symmetry breaking arise not from the vev of a Higgs field but from the boundary conditions of a multidimensional field on a four-dimensional brane. The Lagrangian is symmetric but the boundary conditions are not. This construction allows one to get W and Z bosons as first K-K excitations together with the infinite tower of states which are made heavy by warped geometry. Since one has no scalar fields at low energies, these models are called Higgsless, though scalar fields appear at high energies. What is essential, unitarity is preserved in this case. There is some problem to get masses for chiral fermions. To do this, one puts fermions in the bulk and allows a mass term at the IR vector-like brane which is then translated to chiral fermions on our brane. One has the usual spin 1 K-K states with the couplings slightly different from the SM, and not to contradict the EW tests, one needs a heavy compactification scale.

It should be stressed that all these models, contrary to the SM and its SUSY extensions, are non-renormalizable and are usually treated as effective low-energy ones.

3. Problem #2: New Physics at the TeV scale and search for SUSY

What is the new physics that is waiting for us at the TeV scale? Is it supersymmetry, or extra dimensions, or something else? The answer hopefully will come soon. Meanwhile one should be prepared to discover it. Below I concentrate on SUSY option which is the mainstream for collider experiments of the last decade and in the near future.

Supersymmetry in this context is understood as various versions of the MSSM which differ by the way supersymmetry is broken. All of them have different phenomenological properties and vary in experimental signatures. One usually distinguishes between the following possibilities:

• MSSM (gravity mediation) [13].

This is the most elaborated version. One usually has 5 universal parameters: m_0, $m_{1/2}$, A_0, $\tan\beta$ and $sign(\mu)$ which form the parameter space subjected to various constraints. Generically squarks and sleptons are relatively heavy (though stop and sbottom might be light), gauginos are typically lighter and, depending on the parameter choice, may decay into leptons besides hadron jets. Production cross-sections vary with masses but in some regions are big enough for their detection at colliders. The lightest superparticle (LSP) is usually neutralino which might be light below 100 GeV. In some cases one may have splitting of masses that leads to metastable particles (gluino, stau, stop) which may fly through the detector prior to decay. They may even form exotic states, the so-called R-hadrons where quark or gluino are replaced by their superpartners, though this possibility usually needs severe fine-tuning.

• MSSM (gauge mediation) [14].

This is the next popular version. Due to the other mechanism of SUSY breaking one has a different mass spectrum. The LSP is gravitino which might be very light. Since gravitino interacts only gravitationally, i.e. extremely weakly, the next-to-lightest particle plays an essential role. It is usually neutralino which decays into photon and gravitino: $\tilde\chi^0_1 \to \gamma\tilde G$, i.e. in a final state one gets photons and missing energy. In this case one may have very long-lived SUSY particles, much longer than in the gravity mediation case.

• MSSM (anomaly mediation) [15].

In this case, the mass spectrum of superparticles also differs from that of the universal SUGRA model. In particular, the usual universality condition for gaugino masses at the GUT scale is replaced by the anomaly relation when the gaugino mass ratio is proportional to the beta function coefficients of the corresponding gauge groups which leads to inverse hierarchy of gaugino masses. While the RG running these masses can merge at a lower scale, thus leading to the so-called mirage unification. In this case, like in gauge mediation scenario, one can also have long-lived charged particles which may decay inside the detector.

- MSSM (non-universality).

Universality assumption introduced in the gravity mediation model reduces the number of free parameters, thus increasing the predictive power of the model. However, this is not a physical requirement and can be relaxed. A nonuniversal model naturally allows more freedom and can satisfy further constraints. A recent review of various possibilities can be found in H.Baer's talk at SUSY'06 [16].

- NMSSM (singlet extensions).

Singlet extensions of the MSSM have their origin in solution of the so-called μ problem and as a common feature have additional singlet field(s). Due to some additional freedom here one can relax some constraints and, in particular, increase the value of the lightest Higgs mass above 120-130 GeV. These models predict also new scalar particles besides the usual two Higgs doublets. Many models of this type vary in details. Their summary can be found in V.Barger's talk at SUSY'06 [17].

- MSSM (with R-parity violation) [18].

At last, the R-parity violating models introduce the new lepton or baryon number violating interactions. If these interactions are suppressed, they do not contradict modern limits on rare processes but lead to new phenomena. R-parity was invented in order to stabilize the LSP as a possible candidate for the Dark matter particle, but if LSP is not stable but long-lived, it can still play its role. One should be accurate though in applying these new interactions [19].

Below I consider possible manifestation of supersymmetry at hadron colliders within the framework of the gravity mediated scenario. The allowed region of the MSSM parameter space is defined after applying various constraints. In Fig.2 [20], the projection of the mSUGRA parameter space onto the m_0-$m_{1/2}$ plane is shown for fixed values of $\tan\beta$ and A_0. The left upper corner of the plane is forbidden due to the requirement of neutrality of the LSP, the left bottom corner is forbidden due to the Higgs mass limit from LEP and the $b \to s\gamma$ branching ratio, and the right bottom corner does not allow radiative electroweak symmetry breaking. Accepting the high experimental accuracy of the measurement of the amount of DM from WMAP, one also gets a narrow (blue) band allowing the right amount of DM assuming is to be totally made of supersymmetric particles. Different regions along this band indicated by numbers correspond to different phenomenological consequences.

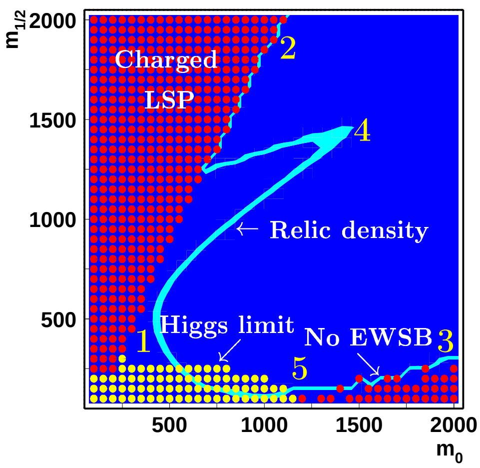


Fig. 2. The allowed regions of the mSUGRA parameter space: bulk region (1), co-annihilation region (2), focus-point region (3), funnel region (4) and EGRET region (5).

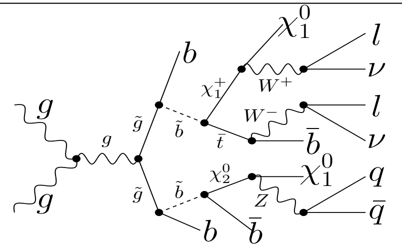
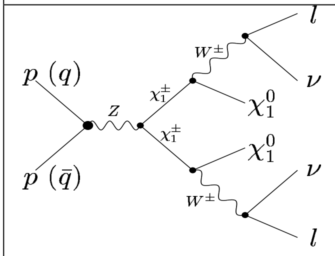
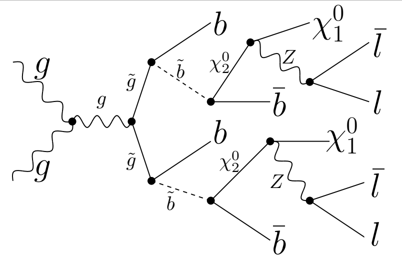
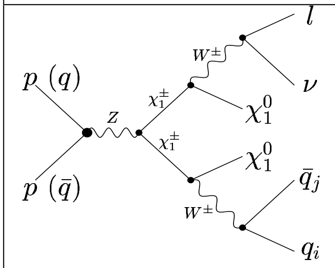
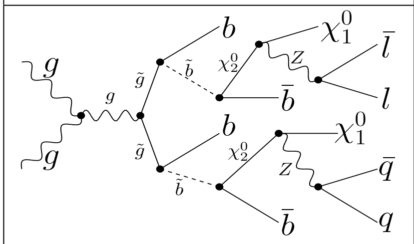
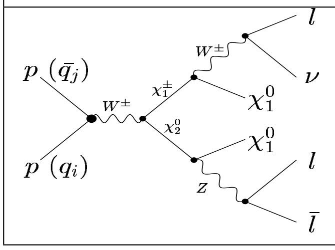
Strong Process	final states	Weak Process	final states
	2ℓ 2ν $6j$ $\not\!\!E_T$		2ℓ 2ν $\not\!\!E_T$
	4ℓ $4j$ $\not\!\!E_T$		ℓ ν $2j$ $\not\!\!E_T$
	2ℓ $6j$ $\not\!\!E_T$		3ℓ ν $\not\!\!E_T$

Table 1: Creation of pairs of gluino (left) and of the lightest chargino and the second neutralino (right) with further cascade decay.

Looking for superpartners at hadron colliders one should have in mind that they are always produced in pairs and then quickly decay creating the ordinary quarks (i.e. hadron jets) or leptons plus missing energy and momentum. For strong interaction the main process is the gluon fusion presented in Table 1 [21]. Fig. 3 shows a typical event inside the ATLAS pixel detector in the cylindrical first layer ($R \approx 4$ cm) [22]. Particles are produced at the collision point and decay almost immediately producing hadron jets and muons accompanied by neutralinos taking away the missing energy and momentum.

Charginos and neutralinos are produced in pairs through the Drell-Yan mechanism and can be detected via their lepton decays $\tilde\chi^\pm_1 \tilde\chi^0_2 \to \ell\ell\ell + \not\!\!E_T$ (see the Table 1). The main signal of their creation is the isolated leptons and missing energy. The main background in trilepton channel comes from creation of the standard particles $WZ/ZZ, t\bar t, Zb\bar b \quad b\bar b$.

The cross-sections at the LHC for various processes in the whole $m_0 - m_{1/2}$ plane are shown in Fig.4 [22]. One can see that they vary from a few hundred pb for gluino production to a few tenth of pb for squark production in the maximum and strongly depend on the point in parameter space.

To illustrate the LHC potential in discovering SUSY we consider a gluino production process with a further cascade decay into jets and muon pairs (process # 2 from Table 1). For the choice of parameters cor-

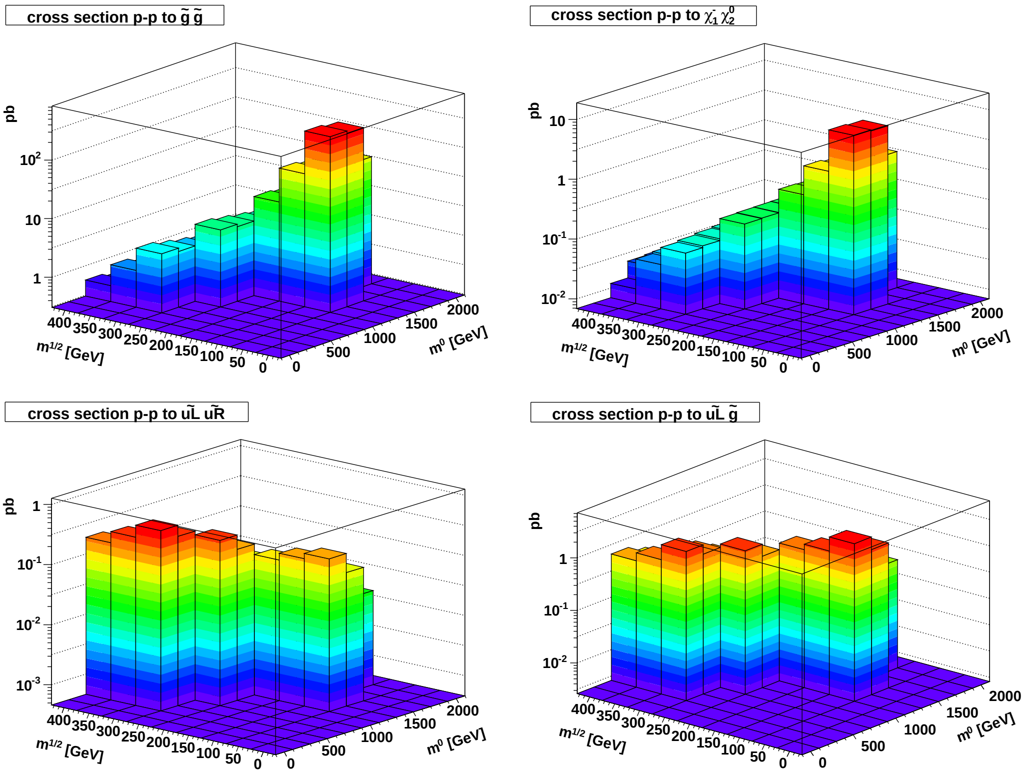


Fig. 4. The cross sections of superpartners creation as functions of $m_{1/2}$ and m_0 for $\tan\beta = 51$, $A_0 = 0$ and positive sign of μ.

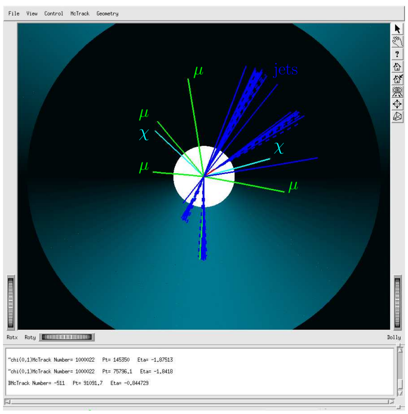


Fig. 3. Generation of the process inside the cylindrical pixel detector in the plane transversely to the beam. One can see 4 muon tracks (green lines), 2 tracks from neutralino (light blue lines), 4 jets (dark blue lines) and one long-lived B-meson (red line)

responding to the region # 5 in Fig.2, the cross-section of gluino production achieves 13 pb; however, branching ratios into muons are small and reduce the total cross-section to a few tenth of fb. In the final state the gluino pair gives 4 b-quarks (b-jets), 4 muons and a pair of the lightest stable neutralinos $\tilde{\chi}_1^0$ giving the high missing transverse momentum. The jets contain the B-hadrons and one may have four secondary vertices, which allows one to reduce the background even at the trigger level. Neutralino takes away quite high transverse momentum. Fig. 5 [22] shows the total transverse momentum of two neutralinos. Careful reconstruction will allow one to detect such a high loss in the total measured transverse energy. The b-tagging of all b-jets appears to be extremely important since the B-hadrons live long enough

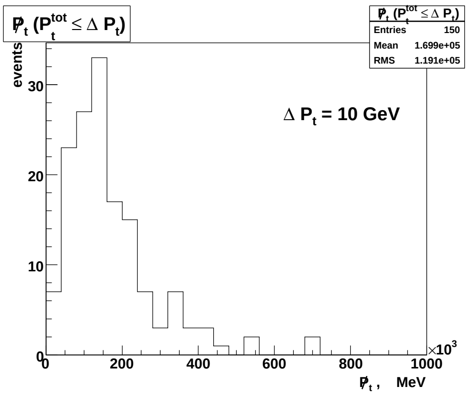


Fig. 5. Total missing transverse momentum P_t of two neutralinos. Event selection is made assuming that the total P_t of gluino pair is less than 10 GeV.

to move away off the creation point. As a result it allows one to observe a secondary vertex of the B-hadron decay at a certain distance from the primary beams collision initial vertex and tag hadronic jets from b-quarks. Fig. 6 shows the distribution of the free path of B-hadrons provided all four B-hadrons have free paths more than 100 μm simultaneously [22]. One can see that 94% of events satisfy this condition.

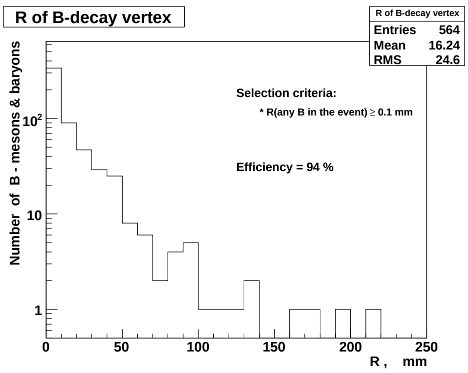


Fig. 6. The free path of B-hadrons before their decay.

It should be mentioned that SUSY event at colliders might be easily mixed up with another possible new physics. For example, in the Little Higgs models one also has missing energy events when extra neutral heavy particles, which are present in the spectrum, escape observation. We show some sample diagrams in Fig.7 [23]. To distinguish between these two possibilities one has to carefully study spin correlations and event rates.

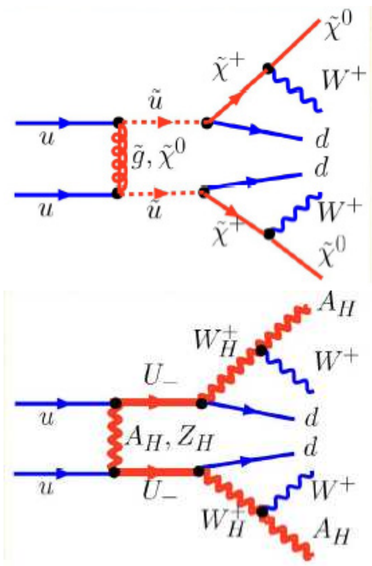


Fig. 7. Comparison of SUSY (up) and the Little Higgs (down) missing energy events at colliders

To present the region of reach for the LHC in different channels of sparticle production, it is useful to consider the same plane of soft SUSY breaking parameters m_0 and $m_{1/2}$. In this case, one usually assumes certain luminosity to be achieved during the accelerator operation. Fig. 8 [24] shows these regions of reach in different channels and different luminosities. The lines of a constant squark mass form the arch curves, and those for gluino are almost horizontal. The curved lines show the reach bounds in different channels of creation of secondary particles. The theoretical curves are obtained within the MSSM for a certain choice of other soft SUSY breaking parameters. As one can see, for the fortunate circumstances a wide range of the parameter space up to the masses of the order of 2 Tev will be examined.

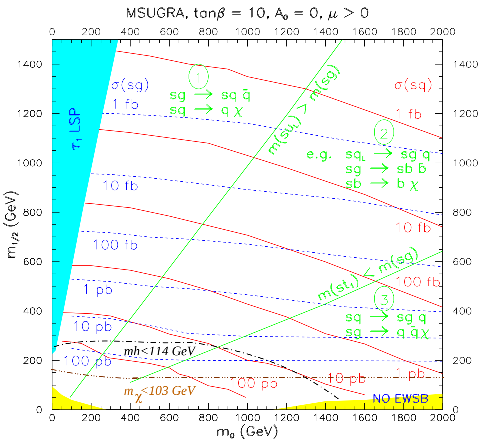


Fig. 8. Expected range of reach for superpartners in various channels and luminosities at LHC

4. Problem #3: The Origin of the Dark Matter

Cold Dark Matter (CDM) makes up 23% of the energy of the Universe, as deduced from the temperature anisotropies in the Cosmic Microwave Background (CMB) in combination with data on the Hubble expansion and the density fluctuations in the Universe [25]. In fact, the existence of the Dark matter in the Universe was known since the late 30's from the motion of clusters of galaxies, rotation curves of stars and more recently from gravitational microlensing experiments. However, the origin of DM remains unclear.

In principle, there are two main options: DM is made of macro objects like brown dwarfs, dust, micro and macro black holes, etc., or it is made of massive weakly interacting elementary particles - the so-called WIMPs. The first option is not favorable from observational data. For the second option we have the following candidates (all of them beyond the SM):

- axion (axino) (strong CP)
- neutralino (SUSY)
- sneutrino (SUSY)
- right heavy neutrino
- gravitino (SUSY)
- heavy photon (LH)
- heavy pseudo-goldstone (LH)
- light sterile Higgs (Inert H)

One may probably add to the list. None of them is observed so far.

There are two ways to detect the DM: direct and indirect. Direct DM detection assumes that the DM particle hits the Earth and interacts with nucleons of a target. With deep underground experiments one may hope to detect such an interaction. There are several experiments available: DAMA, Zeplin, CDMS and Edelweiss. Only DAMA claims that they see the effect in seasonal modulation with fitted mass of around 50 GeV [26]. All the other experiments do not see it. The reason might be in different methodic and different targets, since the cross-section of nucleus-DM interaction depends on a spin of a nucleus. Still, today we do not have convincing evidence of the DM interaction.

Indirect detection is aimed to look for a secondary effect of DM annihilation in the form of extra gamma rays and charged particles (positrons and antiprotons) in cosmic rays. These particles should have an energy spectrum which reflects their origin from annihilation of massive particles and is different from the background one of the known sources. Hence, one should have some shoulders in the cosmic ray spectrum. There are several experiments of this type: EGRET (diffuse gamma rays) to be followed by GLAST, HEAT and AMS01 (positrons) to be followed by PAMELA, BESS (antiprotons) to be followed by AMS02. All of these experiments see some deviation from the background in the energy spectrum, though experimental uncertainties are rather big.

One of the most popular CDM candidates is the neutralino, a stable neutral particle predicted by supersymmetry [27]. In a recent paper [28] we showed that the observed excess of diffuse Galactic gamma rays has all the properties of the π^0 decays of monoenergetic quarks originating from the annihilation of the DM.

The spectral shape of the diffuse Galactic gamma rays has been measured by the EGRET satellite in the range 0.1 - 10 GeV. It allows an independent analysis in many different sky directions. Comparing the background with the EGRET data shows that above 1 GeV there is a large excess of gamma rays which reaches more than a factor of two towards the Galactic centre. However, fitting the background together with the DMA yields a perfect fit in all sky directions for a DM particle mass around 60 GeV as shown in Fig.9.

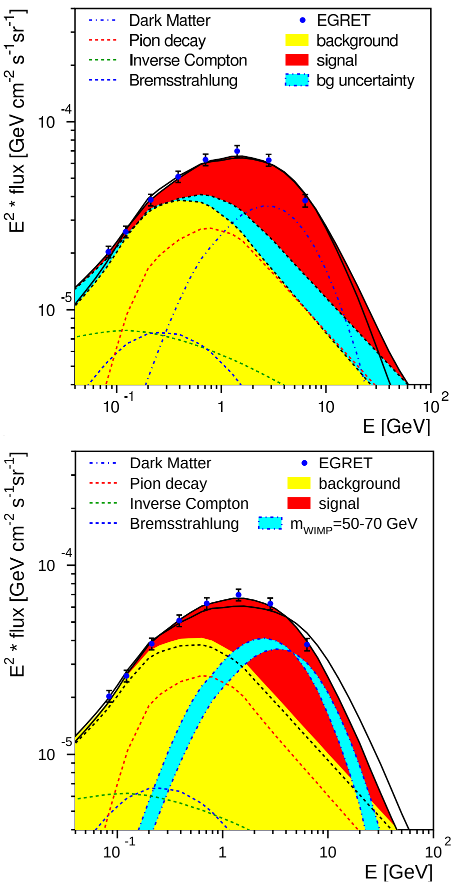


Fig. 9. The EGRET gamma ray spectrum fitted with DM annihilation for $m_0 = 1400$ GeV, $m_{1/2} = 175$ GeV, $\tan\beta = 51$. The possible variation of the background (blue shaded area above) is not enough to accommodate the EGRET signal. The variation of the WIMP mass between 50 and 70 GeV shown by blue shaded area below is allowed by the EGRET data with the conventional background

The distribution of Galactic diffuse gamma rays measured by EGRET over all sky directions allows one to reconstruct the profile of DM in our galaxy and to explain the peculiar shape of rotation curve of stars [28].

This intriguing hint of DMA is compatible with supersymmetry, assuming that the EGRET excess originates from the annihilation of the stable, neutral lightest supersymmetric particles, the neutralinos. Their mass is then constrained to be between 50 and 100 GeV ($m_{1/2}$ between 125 and 175 GeV) from the EGRET data, which strongly constrains the masses of all other SUSY particles, if mass unification at the GUT scale is assumed. Combining the EGRET data with other constraints, like the electroweak precision data, Higgs mass limits, chargino mass limits, radiative electroweak symmetry breaking and relic density leads to a very constrained allowed region of the SUSY parameter space shown in Fig.10. Choosing a point in this region gives the SUSY mass spectrum with light gauginos and heavy squarks and sleptons (see the Table 2).

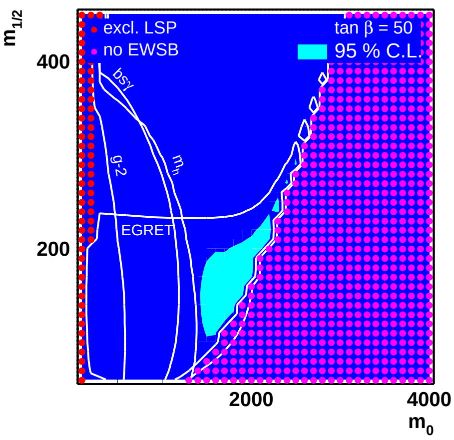


Fig. 10. The allowed regions of the mSUGRA parameter space with account of EGRET data. The light shaded area (blue) indicates the 95% C.L. parameter range allowed by EGRET data, the individual constraints have been indicated by the lines and dots.

The lightest neutralino is an almost pure bino in this case meaning that the DM is a superpartner of the CMB.

Scanning over the allowed region of Fig. 10 and demanding an LSP mass above 50 GeV requires $\tan\beta$ to be in the range of 50 to 55 [29]. The strong dependence of the relic density on $\tan\beta$ originates from the strong dependence of the pseudoscalar Higgs mass.

Particle	Mass [GeV]
$\tilde{\chi}^0_{1,2,3,4}$	64, 113, 194, 229
$\tilde{\chi}^{\pm}_{1,2}, \tilde{g}$	110, 230, 516
$\tilde{u}_{1,2} = \tilde{c}_{1,2}$	1519, 1523
$\tilde{d}_{1,2} = \tilde{s}_{1,2}$	1522, 1524
$\tilde{t}_{1,2}$	906, 1046
$\tilde{b}_{1,2}$	1039, 1152
$\tilde{e}_{1,2} = \tilde{\mu}_{1,2}$	1497, 1499
$\tilde{\tau}_{1,2}$	1035, 1288
$\tilde{\nu}_e, \tilde{\nu}_\mu, \tilde{\nu}_\tau$	1495, 1495, 1286
$h, H, A, H^{\pm}$	115, 372, 372, 383
Observable	Value
$Br(b \to X_s \gamma)$	$3.02 \cdot 10^{-4}$
Δa_μ	$1.07 \cdot 10^{-9}$
Ωh^2	0.117

Table 2: SUSY Particle spectrum at the EGRET point: $m_0 = 1500$ GeV, $m_{1/2} = 170$ GeV, $A_0 = 0$, $\tan\beta = 52.2$, Sign $\mu = +$

Given the mass of neutralino one can calculate the cross-section of its interaction with the nucleus and compare it with the reach of direct search experiments. This comparison is shown in Fig.11 [30]. One can see that the cross-section is two orders of magnitude smaller than the present experimental reach, but will be covered soon by the forthcoming experiments.

5. Conclusion

Future will show us whether we are on the right track and discoveries are waiting for us round the corner or some unexpected reality is going to emerge. Stakes are high. I would like to conclude with quotation from St.John "Blessed are those who believe and yet have not seen"[31].

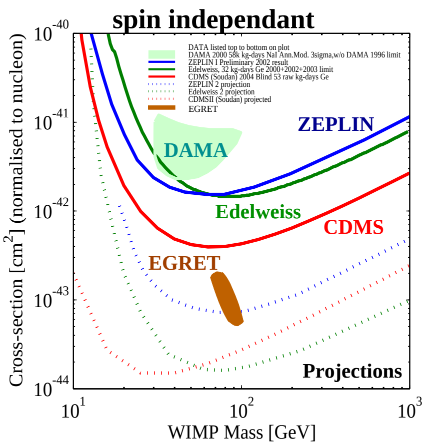


Fig. 11. Cross-section of DM nucleus interaction versus the DM particles mass and discovery reach of various experiments

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